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Impacts of projected precipitation changes on sugar beet yield in Eastern England

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Abstract

Projected increasing temperatures and reduced summer rainfall in the UK pose a sustainability and food security challenge for the agricultural industry. This study investigates the potential impact of precipitation changes on Eastern England sugar beet yield. Precipitation data over Eastern England from weather stations (1971-2000) and a range of CMIP5 climate models (“historical” for 1971-2000; and RCP45 and RCP85 for 2021-2050) were examined. A good agreement was found between the observations and the overlapping model grid cell. The study then investigated the impact of likely future rainfall changes on yield by applying controlled watering regimes informed by the CMIP5 projections to 150 sugar beet plants grown in a greenhouse – the use of CMIP5 projections in this way is a first. Watering regimes that represent “present day” and “future” precipitation characteristics were calculated: 0.46L of water was applied every other day to each plant in the “present day” category; 0.39L was applied every other day to each plant in the “future” category. This reflects the 16% reduction in future rainfall that was calculated from the climate models. Results from the greenhouse experiment showed a statistically significant ($p<0.01$) reduction in soil moisture in the “future” category, which was related to a statistically significant ($p<0.05$) reduction in mean tuber wet mass: mean of 360g for “present day”; and 319g for “future”. The results for dry mass were less significant ($p=0.11$) but indicated a reduction in the future category (95.2g vs. 88.2g). These findings imply a potential yield reduction of 11% by 2050.

Keywords: agriculture; climate change; CMIP5; UK rainfall

1. Introduction

1.1 Precipitation changes and impacts on agriculture

Climate change is one of the biggest challenges facing societies today and reviews of its impacts on agriculture have shown considerably more negative effects than positive (IPCC, 2014). The reason for this is because agriculture is inherently sensitive to climate: any change in climate will almost certainly affect plant growth positively or negatively. These effects are already detectable where, for example, temperature changes have been shown to have an impact on growing season (Menzel *et al.*, 2006). This type of sensitivity is reflected where and when food prices increase following cases of extreme weather events in food producing areas (IPCC, 2014). In the light of this, it is important to understand potential impacts of climate change for different regions to enable the agricultural industries to prepare and adapt to the changes that are likely to occur.

The highest profile agricultural losses occur at the hands of extreme events and in recent years the UK, for example, has experienced a number of extreme rainfall events that have impacted the agricultural community. January and February 2014 in England saw rainfall totals of approximately 150 mm and 109 mm, respectively, which are well above the average rainfall values for these months (Met Office, 2014). This resulted in around 49,000 ha of farmlands being flooded in a single event during February 2014 in Somerset and the Thames and Severn catchments (EFRA Committee, 2014). The extent and duration of this flood resulted in more than 44,000 ha of farmland being underwater for more than one day and 40% of that area (17,800 ha) being flooded for 15 days causing significant damage to the farmland and harvest ready crops, and loss of income to the farmers (DEFRA, 2014).

These extreme events are likely to become more frequent and more intense (IPCC, 2013) but the impact on crop yield from extreme events is difficult to calculate and adapt to: in the isolated regions where the floods occur, yield is reduced to zero but other areas may not be affected. Furthermore, analyses of extreme events over future timescales are likely to be dominated by uncertainty due to the nature of modelling studies (Maraun *et al.,* 2010). Conversely, a more climatological analysis has the potential to produce results that can more confidently be used to plan and adapt operating practices. There are robust signals in climatic variables on the seasonal timescale, including precipitation, which can be used to understand potential future impacts. For the UK, this signal tends to be wetter winters and drier summers (UKCP, 2009; IPCC, 2013). How this will impact agricultural yields requires further investigation.

1.2 Sugar beet production in the UK

Sugar beet in the UK is usually sown between March and April and harvested between September and February (British Sugar, 2011). The tuber contains 15-17% sugar (FAO, 2009) and accounts for 50% of the sugar consumed in the UK. It is an important agricultural crop in the UK: the sugar industry contributes significantly to the UK rural economy and supports around 13,000 jobs in the supply chain (British Sugar, 2011). Approximately 3,000 farmers grow the crop, predominantly in Eastern England, on over 170,000 ha of farmland (British Sugar, 2011).

Sugar beet productivity in the UK is increasing: annual farmer delivered yield between 1976 and 2004 increased by 111 kg/ha (Jaggard *et al*., 2007). Further, British Sugar (2011) reported an average increase of 11 tonnes of sugar beet per hectare (an approximate increase of 60% between 1981 and 2011). These increases are generally assumed to result from improved agronomy, seed variety and favourable weather, but these assumptions cannot be justified without taking the climate related changes and local weather patterns into consideration. According to IPCC (2013), warming of the climate system is unequivocal and has resulted in a lot of changes in the climate system with positive and negative impacts on agriculture. Therefore, it is important to factor climate and weather related variables into yield analysis.

The most important economic aspects of sugar beet for farmers are the size of the root yield and its sugar content, which are influenced by a number of environmental factors, including weather patterns and soil conditions. Sugar beet farming in England is over 95% rain-fed with the use of irrigation being minimal (British Sugar, 2011). Water volume and timing is critically important to the successful growth of sugar beet plants, as indicated by Richter *et al.* (2006) who modelled the variability of UK sugar beet under climate change using a regional climate model. They found that water will be a major stress factor in the future and that relative soil moisture will be reduced under high greenhouse gas emissions scenarios. The analysis presented in the paper here extends the work of Richter *et al.* (2006) by using daily precipitation projections from a climate model ensemble to inform a controlled watering experiment in a greenhouse, which is relevant to potential future rainfall conditions in East England under medium and high greenhouse gas emissions scenarios.

In Europe, sugar beet yield is generally seen to decrease when stressed via low water conditions: Pidgeon *et al.* (2001) estimated potential sugar beet yield losses, calculated from climate and crop model projections due to water stress, vary between 15% and 30% for England. Given the nature of UK sugar beet production, past and present water limitations have most likely been driven by changes in rainfall patterns. Furthermore, many past studies have indicated that sugar beet is, more specifically, sensitive to water supply in terms of: yield (e.g. Jones *et al*., 2003, Richter *et al*., 2006, Kenter *et al*., 2006, Choluj *et al*., 2014); storage root formation (e.g. Brown *et al*., 1987; Rytter, 2005); and leaf growth (Rytter, 2005).

As sugar beet is economically significant in the UK and is sensitive to water supply, we consider it an ideal crop to investigate in the context of future changes in precipitation. Furthermore, there are currently no sugar beet growing experiments in the literature that are informed by ensemble model projections – one of the aims of this paper is to address this.

1.3 Aims and scope

The main aim of this study was to understand the impact of climatological precipitation changes in Eastern England on sugar beet yield. State-of-the-art ensemble climate model projections will be used to inform a greenhouse experiment in a novel way. In this paper, the following results are presented and interpreted:

- An examination of precipitation data from weather station observations and climate model projections for Eastern England;
- A series of watering regimes, calculated from the precipitation examination, which represent the climatological precipitation levels delivered to Eastern England for “present day” and “future” climate scenarios; and
- Measures of sugar beet productivity from a greenhouse experiment, where 150 sugar beet plants were grown with the application of the calculated watering regimes.

This investigation only considered climatological changes in the precipitation over the sugar beet growing season. Wet and dry tuber mass were used as the main measure of sugar beet productivity. The changing nature of precipitation event size and frequency, and the sugar concentration of the tubers, were not examined in this study. Furthermore, this work only considers the impact of the different watering regimes on the plants once they were developing a tuber; all plants were treated equally through the germination and juvenile stages so that the impact on yield could be assessed and not the impact on germination. Furthermore, the historic, longer term relationship between farm yield data and precipitation was not investigated here.

2. Data, materials and methods

2.1 Precipitation: weather station observations and climate model projections

The present day precipitation regime for Eastern England was determined from 6 weather stations that have operated in the region for periods greater than 30 years with little or no missing data. These are: Terrington St Clement (2 m above sea level (asl), 0.29 ° E, 52.745 ° N); Santon Downham (6 m asl, 0.675 ° E, 52.458 ° N); Coltishall (17 m asl, 1.356 ° E, 52.756 ° N); Writtle (32 m asl, 0.432°E, 51.733°N); Manston (44 m asl, 1.35°E, 51.35 N); and Stansted Mountfichet (70 m asl, 0.184°E, 51.897°N). See Figure 1 for the locations of these weather stations. All the analyses of precipitation data in this study only considered the key growing period for sugar beet (i.e. May-October).

To determine the likely climatic changes over Eastern England, precipitation projections from a range of climate models were examined. The projections were taken from the 5th Phase of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012). Data were used from three different CMIP5 experiments, two of which aim to assess the impact of different levels of greenhouse gas emissions over the 21st Century: the Representative Concentration Pathways (RCPs; van Vuuren *et al.*, 2011). The RCP45 and RCP85 scenarios were used for the period 2021-2050 – this temporal window was used as it is of interest to the sugar industry for future planning (British Sugar, 2011). These RCPs represent mid-range (RCP45) and high-end (RCP85) impacts on radiative forcing changes in the future, respectively. The third experiment used was called “historical”, which provides a benchmark period that allows the model data to be compared with observations. This was used for the temporal window of 1971-2000. For each CMIP5 experiment, a multi-member ensemble of model runs was used. The individual members of the ensemble were initiated using slightly different, though equally realistic, initial conditions for each of the model runs in order to capture some element of internal climate variability – see Taylor *et al.* (2012) for further details.

The particular models examined here had to meet the following criteria: the model should be an Earth System Model (ESM) or a Coupled General Circulation Model (CGCM); daily precipitation data for the “historical”, RCP45 and RCP85 experiments should be available; and the experiments should have been run as ensembles. Table 1 gives details of the models that met these criteria. Data from these models were retained for further analysis based on how closely they replicated precipitation observations for the region (see Section 3).

2.2 Calculation of water regimes

The aim of this work was to investigate climatological changes in precipitation from climate model projections. In this respect, the watering regimes were not designed to replicate realistic precipitation events. Instead, they delivered the total growing season (i.e. May-October) precipitation in a series of regular and equal watering events. In short, all the plants were watered every other day (i.e. watering day – dry day – watering day – dry day and so on) with the same amount of water per watering day for each watering regime.

There was a “control” watering regime where precipitation observations for the period 1971-2000 and the recommended level of water for a successful sugar beet crop from the Food and Agricultural Organisation of the United Nations (Brouwer and Heibloem, 1986) were used to calculate the watering event size. Secondly, there was a “future” watering regime, which was based on a modification of the “control” regime watering event size determined by the growing season (i.e. May-October) changes in precipitation from the RCP45 and RCP85 CMIP5 climate projections for the period 2021-2050.

Plants were allocated into the “control” or “future” watering regimes and the different watering regimes were implemented after the plants had reached their 10-12 leaves growth stages and had started forming tubers. To account for natural variability in plant sizes, the plants assigned to each watering regime were selected to result in an equal distribution of plant sizes in each watering regime. Allocation of plants to the watering regimes was done at this time to coincide with the rainfall analysis from May to October for the study periods and also because the biggest rainfall changes are projected for the summer. Changes in rainfall from the analysis conducted were imposed on the plants in the future category, which had a reduction in rainfall amount.

2.3 Plant variety

Apart from the effect of growing conditions, yields are also influenced by the chosen variety of seeds. Some varieties have high tuber yields but low sugar percentage while others may have low yield with high sugar percentage (BBRO, 2013). Pelleted sugar beet seed of the same variety (SY Muse) were used for all replicates in this experiment. According to the British Beet Research Organisation (BBRO, 2013), SY Muse is a high yielding variety that performs consistently well with excellent establishment and resistance to drought and rhizomania and it is widely used by UK farmers. SY Muse compares favourably well with other varieties and is third on the official yield variety list of the BBRO (2013) in terms of root yield and sugar content. It is rated “3” and “4” on a scale of 1 to 9, with 1 being “susceptible” and 9 being “tolerant” on the BBRO (2013) rust and powdery mildew disease scales, respectively. As SY Muse is not extreme on these scales, this was considered further justification for its use in this experiment.

2.4 Greenhouse experiment

The sugar beet plants were grown in individual pots in a greenhouse located on the Brunel University London campus. The greenhouse is an ideal environment for the experiment as it allows the watering to be controlled. Temperature and humidity were not controllable in the greenhouse but these variables were consistent for the different watering regime groups. Furthermore, once classified into the different watering regimes, the plants were distributed systematically around the greenhouse so there would be no bias in temperature, humidity or sunlight for any group.

The sugar beet seeds were sown into 150 plastic 33 L plant pots with two seeds per pot in the greenhouse on the 15 April 2014. 30 kg of “John Innes No. 2” compost per pot was used as the planting medium. The soil in the pot was shaken to eliminate pockets of air in the soil and keep the soil level and compact. This enabled the soil to retain moisture after draining off excess water. The timing of watering is important to maximise yields and ensure a fair comparison between the watering regimes. Water was applied in the mornings when the plants can maximise the available water because of lower evapotranspiration. A watering procedure was used that ensured the water was added in a consistent way to all pots and was as uniform as possible around the surface area of the soil.

This method was successful in terms of germination: 298 seedlings emerged out of the 300 seeds sown. Plant seedlings were thinned at their 4-6 leaves growth stages from two to one seedling per pot to encourage uniform establishment.

As described in Section 2.2, the plants were subsequently classified into the “control” and “future” watering regimes at the 10-12 leaf growth stage. The pots for the plants in each regime were colour coded and colour coded measuring cylinders were used to add the water so that the potential for human error was reduced to a minimum. Each plant was assigned a number so that growth and yield parameters could be recorded for specific plants.

In the greenhouse study, a number of non-destructive parameters were used to assess the yield potential of the plants over the growing season including: the number of leaves; height of the plants (i.e. height of the tallest stem); the growth ratio of the plants (i.e. height divided by number of stems); leaf width (i.e. width of the widest leaf); and soil moisture. The above-ground parameters were measured with the use of a tape rule while below-ground the soil moisture was measured using a Soil Moisture Meter (Lutron Professional PMS-714). These parameters were measured every 2 weeks to enable the examination of water reduction on the plants' development and productivity; this can place yield in the context of the growing season examined.

At the end of the experiment, destructive measurements were taken to determine the mean mass of the tubers as harvested and when dried. When harvested, the tubers were uprooted from the soil and washed. Thereafter, the leaves of the plants were cut off from the crown leaving the tubers, which are of most interest in this research. Each individual tuber was weighed without the leaves – these measurements are reported here as the "wet" weight. The tubers were then labelled with their numbers and put in open transparent bags so that the yield data could be added to the database of growth parameters recorded over the growing season. Analysis of the dry weight of the tubers was conducted using a laboratory method to remove the moisture content. Obtaining the dry weight was done by cutting each tuber into smaller pieces to speed the drying rate. The size of the pieces was kept as equal as possible for all tubers so that drying rates were as equal as possible. A tuber of median size was cut into 8 pieces whereas larger (smaller) tubers were cut into more (fewer) pieces. The pieces were put into individual aluminium trays and numbered for identification purposes and then put inside an oven for drying at 80 °C until constancy, *as per* Mohammadzadeh and Hatamipour (2010). The cut tubers were weighed periodically, typically every 2 hours, until there was no more appreciable change in weight. At this point the value was recorded as the "dry" weight.

Measurements and data collected at different stages of the plants' growth, and following harvest, were statistically analysed to enable quantification of impacts. All measured parameters were tested for normality, which then determines the type of statistical test to be carried out. Parametric tests were conducted where data was normal and non-parametric tests were conducted where data was skewed. Following this, a two tailed t-test was carried out for the two watering regimes. The outcome of the experiment was assessed using the null hypothesis: "there is no difference in the categories". Therefore, applying a confidence interval (CI) of 95% with alpha set at 0.05%; the p-value then gives an indication if significant differences exist in the parameters assessed.

3. Results

3.1 Precipitation analysis

Figure 2 shows the comparison of the "historical" phase of the CMIP5 data with the local weather station data. The precipitation characteristics of the majority of the stations show a good agreement across the region. Only the median and distribution of Manston look different to the other stations – Manston, however, is not representative of the region where most of the farming occurs (Figure 1) so this difference was not considered important. 3 of the CMIP5 model medians are very similar to median values of the stations that represent the farming region. These 3 models – CCCma, MOHC and EC-Earth – will be discussed further whilst the remaining 5 were rejected at this point.

The range and distribution of the modelled precipitation from these 3 models are not as wide as those of the observations but this is to be expected as models do not represent the extremes of precipitation variability well (Maraun *et al.*, 2010). Again, this is not seen as a problem here as we are examining mean conditions and not extremes. Nonetheless, the distribution of precipitation from the MOHC HadGEM2-ES model is much closer to that of the observations than the CCCms and EC-Earth models. Therefore, the MOHC HadGEM2-ES projections will be used in further calculations in this paper. Furthermore, Brands *et al.* (2013) and McSweeney *et al.* (2014) have shown that MOHC HadGEM2-ES generally outperform other models in Europe.

Calculation of the "control" daily mean watering amount was based on the mean seasonal water requirements of sugar beet plants and the mean number of sugar beet growing days, as reported by Brouwer and Heibloem (1986). The mean daily water value was calculated in terms of mm day^{-1}, which was then converted into a volume in litres that would be applied to the plants by multiplying the area of the compost at the level of the surface (mm^2) by the precipitation value (mm day^{-1}) to get a volume per day. In practice, the plants were watered every other day with two times this volume. The values in mm^3 are converted to litres (L) by dividing the results by 1,000,000. Using this method, the "control" watering regime was calculated as 0.230 L day^{-1}, or 0.46 L every other day

Figure 3 presents the ensemble means of May-October precipitation data from the CMIP5 "historical", RCP45 and RCP85 experiments for the 3 models identified as representing the observations well. All the projections indicate that UK rainfall decreases in the models, apart from RCP85 in EC-Earth. Of these models, MOHC HadGEM2-ES shows the largest negative changes in precipitation. Therefore, and further to the reason outlined above, the MOHC HadGEM2-ES data will be used as the basis for the “future” precipitation calculations so that a plausible but relatively extreme scenario is being investigated – this is a scenario that may stress the UK industry so it worth investigating.

Table 2 shows that the difference between the RCP45 and RCP85 experiments was minimal. As a result, two watering regimes were used: “historical”, or “control”; and “future” (i.e. the mean of RCP45 and RCP85). Statistical analysis showed a significant difference (reduction) of 15.8% between the “historical” (1971-2000) and the “future” (2021-2050) regimes. This 15.8% reduction in precipitation from 1971-2000 to 2021-2050 was applied to the calculated watering amount for the “control” group to give the value for the “future” watering regime as 0.195 L day^{-1}, or 0.39 L every other day

These watering quantities were applied to the two watering regime groups from 7 June 2014 (i.e. when the plants reached their 10-12 leaf stage) until harvesting on 23 November 2014 (i.e. growing day 220, which was used in the calculation of the watering regime). The growth of the plants was measured with a tape rule and observations showed that the plants’ leaf formation occurred early (see also Scott and Jaggard, 1993; Kenter *et al*., 2006); but increased steadily in multiples of two throughout the growing season.

3.2 Non-destructive measurements

Table 3 shows the means of the final set of non-destructive measurements taken. Only the final values are presented here because these data give an indication of the ultimate effect of the different watering regimes. In all cases, the “control” group had higher values than the “future” group but the difference between the groups was not statistically significant.

3.3 Wet yield

All the sugar beet tubers were harvested on 23 November 2014 (Day 220). The mean “wet” tuber mass was calculated for both regimes with the “control” having a mean tuber wet weight of 359.5g and the “future” with 318.5g. Figure 4a shows the boxplot of the wet yield data and Figures 4b and 4c show histograms of the complete data sets, which clearly have different distributions. An independent sample t-test was performed on these data with the hypothesis that there is no difference in the mean tuber mass of the “control” and “future” watering regimes. These calculations were based on mean statistics and normality of data with a 95% confidence interval. The result shows that a statistically significant difference existed in the yield of the “control” and “future” watering regimes with a p-value of 0.034, with the future category showing a reduction in yield compared to the control.

3.4 Dry yield

Figure 5a shows a boxplot of the dry weight matter and Figures 5b and 5c show histograms of the “control” and “future” data sets. Statistical analysis of the dry weight showed that the control group had a mean of 95.2g (73.5% reduction from the “wet” weight) and the future group a mean of 88.2g (72.3% reduction). This result equated to a p-value of 0.11 with a null hypothesis that there was no difference between the watering regimes. This indicates that the statistical significance of this result is just outside of the 10% level often applied to determine significance. This, by implication, suggests that the difference in mass is a result of the different moisture content in the tubers of both watering regimes. Despite the lack of a statistical basis for rejecting the null hypothesis, there are still differences worthy of comment. In particular, the largest tubers from the “control” group (i.e. greater than 150g) are absent from the “future” group and the mean for the “future” group is noticeably lower.

3.5 Soil moisture

The mean growing season (May-October) soil moisture data collected during the watering regimes is shown in Figure 6a and the mean monthly soil moisture data are presented in Figure 6b. The difference between the two watering regimes was assessed using the null hypothesis that there was no difference in the two groups. The result of the independent sample t-test carried out using a 95% confidence level showed a significant reduction in the level of soil moisture in the future category with a p-value of 8.7×10^{-06}. In short, the analysis showed that the future group had a significant reduction in soil moisture.

To further examine the impact on yield, the relationship between soil moisture and wet tuber mass was examined using the Pearson Correlation test. This showed that 43% of the variability in wet mass in the “control” group could be explained by the variability in soil moisture. Conversely, 57% of the variability in wet mass in the “future” group could be explained by the variability in soil moisture. In summary, there was a strong negative linear relationship between the yields and soil moisture in the experiment.

4. Discussion

The findings from this study suggest that a potential change in future precipitation, as interpreted from the medium and high greenhouse gas emissions scenarios (RCP45 and RCP85) in an ensemble of MOHC HadGEM2 daily mean precipitation data, is likely to reduce sugar beet yield in the UK by 2050. The mean daily precipitation analysis result from May to October for the two different time slices under “historical” (1971-2000) and “future” (2021-2050) categories in this research showed a 16% reduction in mean daily rainfall for the “future” group. The output from the individual ensemble members showed slight differences but when combined together they clearly reflect a reduction in future rainfall. This result is consistent with the result reported by UKCP (2009) of future reduction in UK summer rainfall. This is an important development for research into sugar beet as its primary growing season is in the spring/summer time and this study represents one of the first times that CMIP5 climate model data has been used to inform a greenhouse experiment.

These results raise questions regarding the viability of the sugar beet industry in the UK, which depends on 95% rain-fed production (British Sugar, 2011), particularly in terms of water resources. This is against a background of EU policy changes that potentially undermine the economic model for the industry (Burrell *et al.,* 2014). The combination of these challenges raises questions about the future of particular agricultural practices and, therefore, calls for creative and innovative adaptation strategies. However, this will depend on the impacts of climate change in other key growing regions, which have not been considered here.

The sowing, growing and harvesting of all the sugar beet plants was carried out under the same environmental conditions but separate watering regimes. The watering regimes were devised based on FAO recommendations of average water need for a sugar beet plant during the growing season (Brouwer and Heibloem, 1986) and precipitation observations from weather stations in Eastern England, which is the dominant production region of sugar beet in the UK. Emergence and establishment was excellent with 298 pairs of cotyledonary leaves emerging out of the 300 seeds sown. All plants were grown under the same water management regime until the plants were categorised into the different treatments; this occurred when they started forming tubers. Ideally, temperature and humidity would also have been controlled but, given that all plants experienced the same conditions, the experimental design is sound in its aim to test the impact of different watering regimes.

General observations of the plants throughout the season showed that early sowing, adequate watering and radiation capture aided full canopy development with the leaves completely shading the pot circumference. Achieving full canopy cover is likely to have helped improve plant and tuber growth (Kenter *et al*., 2006). The role of watering in the plants' tuber development is key and, therefore, a 16% reduction in future rainfall will seriously challenge sugar beet production. The impact of water reduction was measured via the number of leaves, width blade of leaves, plant height, soil moisture and the wet tuber mass.

Overall, the plants in each watering regime were exposed to the same environmental conditions with the plants in each watering regime evenly distributed throughout the greenhouse. The amount of sunlight on different sides of the greenhouse varied, for example, but the systematic distribution of the members of each watering regime meant that there was no bias in such uncontrolled variables. Moreover, the parameter measurement only commenced after the plants had started forming tubers after their juvenile stages. Therefore, the real progress of the tubers can be estimated from the changes in the tubers in both watering regimes and places yield in the context of the mean growing season conditions.

Event based impacts resulting from changes in weather patterns such as high temperatures, had negative impacts on the plants. During high temperature events, the leaves wilted and went into early senescence; Lambers *et al.* (1988) report that such water stress affects the growth and productivity of sugar beet and would have affected the plants in this study. The high temperatures in the months of June and July (Met Office, 2016) drove this problem, with leaves from the bigger plants wilting at the first signs of stress and the leaves from the smaller plants wilting later. This was reported by Hsaio (2000) in a previous study that showed large leaves are usually the first to diminish at the first sign of water stress. Importantly, the wilting of the leaves did not affect one watering regime more than the other and, therefore, the results of the experiment were not biased by the extreme weather events. In spite of this, plants from both categories exhibited remarkable characteristics of adaptability in their high rate of recovery after watering following each stress episode. Figure 6b shows the impact that the high temperature had on soil moisture in July. It is important to discuss wilting because the leaves capture the energy that is converted to sugar and, in so doing, play a key role in the final yield of the crops. Hsaio (2000) reported that a number of plant functions are affected under water stress conditions but the leaves are usually the first to be affected by wilting. Milford and Lawlor (1976) claimed that the younger leaves remain turgid until the stress becomes severe which is supported by observations from the current study. Other studies have shown that sugar beet can exhibit signs of retardation of leaf area increase emanating from temporary drought during the different stages of development. Choluj *et al.* (2004) reported a 6% reduction in relative water content of young and old leaves while Mohammadian *et al.* (2005) reported a loss of 14.1% in leaf area index of sugar beet plants as a result of water stress. Scott and Jaggard (1993) indicated in their study that one of the components to determine sugar beet yield is the amount of radiation it intercepts through the leaves and Choluj *et al.* (2014) more recently observed a 60% and 70% decrease in the leaf area index of some sugar beet genotypes as a result of water deficit compared to their control experiment.

The impact of water stresses will be further compounded by predicted increases in temperature and rising levels of carbon dioxide. By the year 2050, the atmospheric CO_2 concentration is likely to exceed 500 ppm (IPCC, 2013) and, all other things being equal, this increase may result in an increase in yields of C3 crops, including sugar beet, of 13% (Jaggard *et al.,* 2010). However, the continued increase of CO_2 and its impact on other variables will, after a point, cause a decrease in the quality of the sugar beet (Myers et al., 2014). Additionally, future predicted increases in temperature by 2050 will increase evaporation during the growing season, especially in the months of June and July, which will be challenging for sugar beet production and will require further research into water management to maintain and sustain productions in order to maximise yields. Again, more complex experimental procedures, with further variables being controlled, could answer more complex questions but the results reported here are robust and address a fundamental issue in a controlled way.

The yield of the different watering regimes showed a statistically significant ($p<0.05$) reduction in "future" wet yield. Figures 4a and 4b-c show the box plot and the distribution of the mean wet tuber mass from the "control" and "future" watering regimes, respectively. The different watering regimes did result in a statistically significant impact on the root yield between the two groups. This result is in line with Kenter *et al.* (2006) who showed that dry root matter in field studies towards the end of a growing season depended on the availability of water in the soil. Analysis of the bi-weekly soil moisture measurements showed a statistically significant difference between the two groups. These results confirm that the experimental design had a direct impact on the growing environment, which was then reflected in the "wet" yield data: the mean mass of the "control" category was 359.5g; the mean in the "future" group was 318.5g. This is consistent with Richter *et al.* (2006), who modelled the response of UK sugar beet under climate change and found that water will be a major stress factor in future and relative soil moisture will be reduced under a high greenhouse gas emissions scenario.

The "dry" mass of plants in both groups did not indicate a significant difference (p=0.11). This implies that the difference in the tuber mass of both groups was, to a certain extent, a result of water retention. There was, nonetheless, a noticeable difference in the mean of the two groups, which would have been mostly linked to sugar content because once the water has been removed from the tuber, the majority of the remaining mass will be sugars.

A recent study conducted by Chami *et al*. (2015) on the economics of irrigating wheat in East England reported that the use of supplementary irrigation by farmers will be justified by increase in yields. The study asserts that the increment in yield from irrigation will be more beneficial in dry years and in reducing inter-annual yield gaps. Results from the current study align with the result of Chami *et al.* (2015) study in considering irrigation as a management option for sugar beet farmers in order to remain viable in future growing seasons. However, no statistically significant evidence is presented here that suggests sugar content would increase with the implementation of irrigation.

This result shows that under a future of warmer and dryer summers, and all other things being equal, yields will reduce unless other alternatives such as irrigation are considered. Investigations into the effect of other variables are also required. Nonetheless, the observations from this experiment also show that sugar beet is relatively resilient to increased temperatures and that the overall sugar content of the crop is not particularly sensitive to a moderate (16%) decrease in seasonal water availability.

5. Conclusions

The experimental implementation of a 16% water reduction applied to sugar beet plants grown in a greenhouse implies that reduced summer rainfall will have a significant impact on soil moisture (12% decrease; $p<0.05$) and "wet" sugar beet yield (11% decrease; $p<0.05$). This relatively small "precipitation" decrease was calculated from a comparison of the MOHC HadGEM2-ES CMIP5 daily precipitation field of the mean of the medium and high greenhouse gas emissions scenarios (RCP45 and RCP85; 2021-2050) with model output from the "historical" phase (1971-2000).

The result for "dry" yield did not show a statistically significant result (7.4% decrease; p=0.11) but it is a far from conclusive acceptance of the null hypothesis. This is a key result for understanding the how the UK sugar beet industry needs to adapt to future climate changes and work to determine what proportion of this yield decrease is linked to sugar content is underway during a second experimental season using the same greenhouse facility.

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Tables

Table 1: Details of the CMIP5 models examined in this paper.

Model name	Resolution (lat x long)	Institution
CanESM2	64 x 128 (2.8 x 2.8)	Canadian Centre for Climate Modelling and Analysis (CCCma), Canada
CSIRO-Mk3.6.0	96 x 192 (1.875 x 1.875)	Commonwealth Scientific and Industrial Research Organisation (CSIRO) in collaboration with the Queensland Climate Change Centre of Excellence (QCCCE), Australia
HadGEM2-ES	145 x 192 (1.25 x 1.875)	Met Office Hadley Centre (MOHC), UK
EC-EARTH ESM	160 x 320 (1.125 x 1.125)	EC-Earth consortium; data managed by the Irish Centre for High-End Computing (ICHEC)
IPSL-CM5A-LR	96 x 96 (1.875 x 3.75)	Istitut Pierre-Simon Laplace (IPSL), France
MIROC5	128 x 256 (1.41 x 1.41)	Atmospheric and Ocean Research Institute, Japan
MPI-ESM-LR	96 x 192 (1.875 x 1.875)	Max Planck Institute for Meteorology (MPI-M), Germany
CCSM4	192 x 288 (0.94 x 1.25)	National Centre for Atmospheric Research (NCAR), USA

Table 2: MOHC HadGEM2-ES precipitation data analyses for the sugar beet growing season (May-October).

Experiment	Period	Mean daily precipitation (mm day^{-1})	Difference from "Historical" (%)
"historical"	1971-2000	1.625	0
RCP45	2021-2050	1.352	-16.8
RCP85	2021-2050	1.382	-14.9
Mean of RCP45 and RCP85	2021-2050	1.368	-15.8

Table 3: means +/- 1 S.D. of the final measurements of non-destructive parameters from the control and future watering regimes.

Parameters	Control (Mean +/- 1 S.D.)	Future (Mean +/- 1 S.D.)
Highest tip of plants (cm)	49 ± 8.8	41.4 ± 10.43
Number of leaves	34.3 ± 7.2	31.0 ± 7.5
Growth Ratio (cm)	1.5 ± 0.3	1.4 ± 0.1

Leaves width (cm)	10.0 ± 2.2	9.6 ± 2.3
Seasonal Soil Moisture (%)	19.3 ± 1.6	18.0 ± 2.1

Figure captions

Figure 1: Map of the study area. The locations of the weather stations examined in the analysis are plotted. The dashed line indicates the area covered by the MOHC HadGEM2-ES model grid cell used here.

Figure 2: Boxplot of the daily May-October precipitation data for 1971-2000 from the "historical" phase of the CMIP5 climate models and the daily weather station observations for the same period. The thick black line represents the median (2nd quartile) of the distribution. The extremes of the box represent the 1st (bottom) and 3rd quartiles (top). The whiskers indicate the lowest and highest values. Santon Downham had 9 days of missing data in 1983. Manston had 37 days of missing data in 1999.

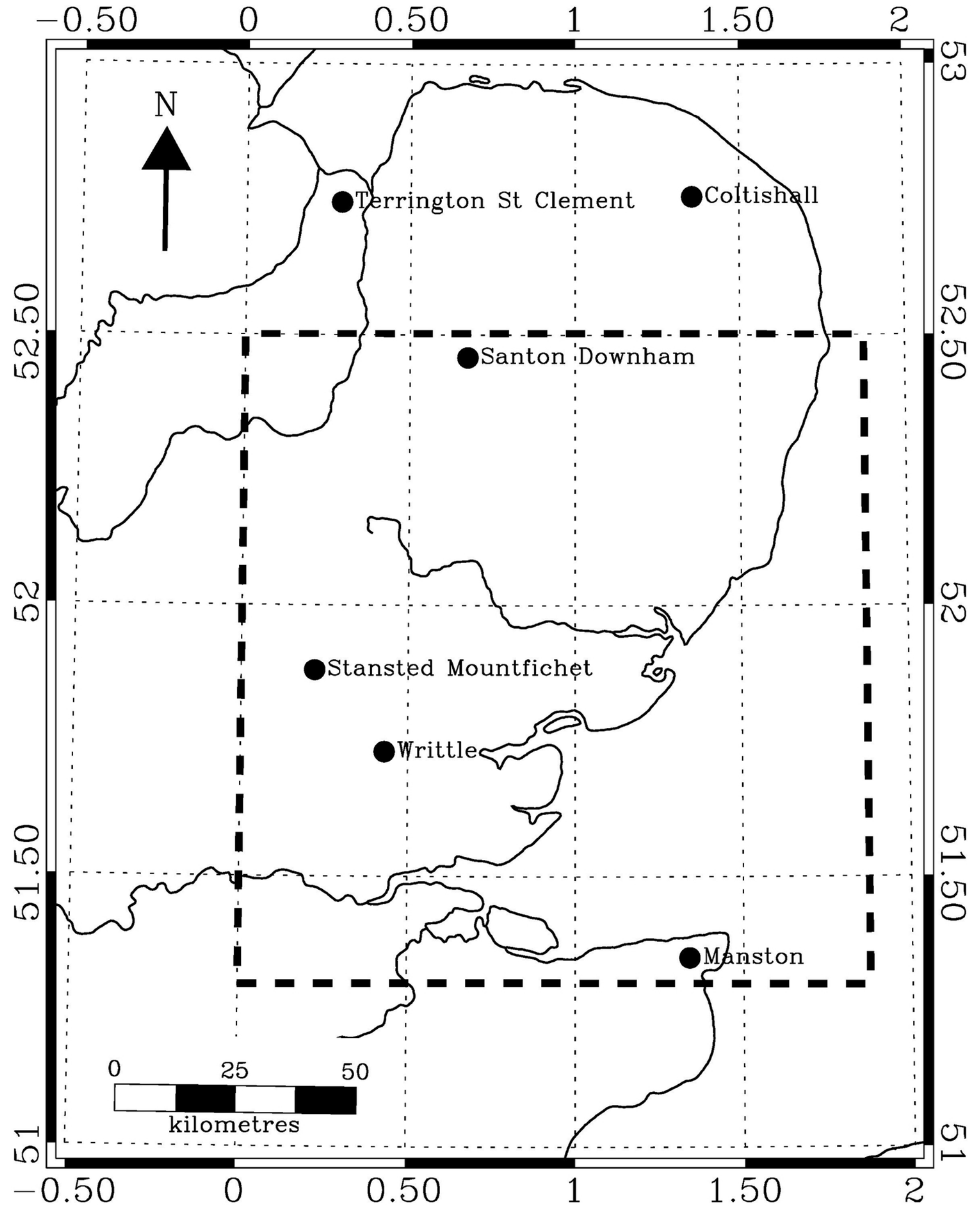
Figure 3: Boxplot of the daily May-October precipitation data from the a) "historical" (1971-2000), b) RCP45 (2021-2050) and c) RCP85 (2021-2050) output from the CCCma, MOHC and EC-Earth climate models. The boxplot details are the same as for Figure 2.

Figure 4: Results of the tuber "wet" mass data analysis. a) Boxplot showing the tuber "wet" mass data from the "control" and "future" categories. The boxplot details are the same as for Figure 2. b) Histogram showing the distribution of the "wet" mass data for the "control" category. c) Histogram showing the distribution of the "wet" mass data for the "future" category.

Figure 5: Results of the tuber "dry" mass data analysis. a) Boxplot showing the tuber "dry" mass data from the "control" and "future" categories. The boxplot details are the same as for Figure 2. b) Histogram showing the distribution of the "dry" mass data for the "control" category. c) Histogram showing the distribution of the "dry" mass data for the "future" category.

Figure 6: Results of the soil moisture data analysis. a) Boxplot showing the soil moisture data from the "control" and "future" categories. The boxplot details are the same as for Figure 2. b) Line graph showing the mean monthly soil moisture measurements for the "control" category (solid line) and the "future" category (dashed line).

Figure 7: Scatter plot showing the "wet" mass for individual tubers from the "control" (filled circles; solid line) and "future" (open squares; dashed line) categories plotted against the mean soil moisture data for each replicate.



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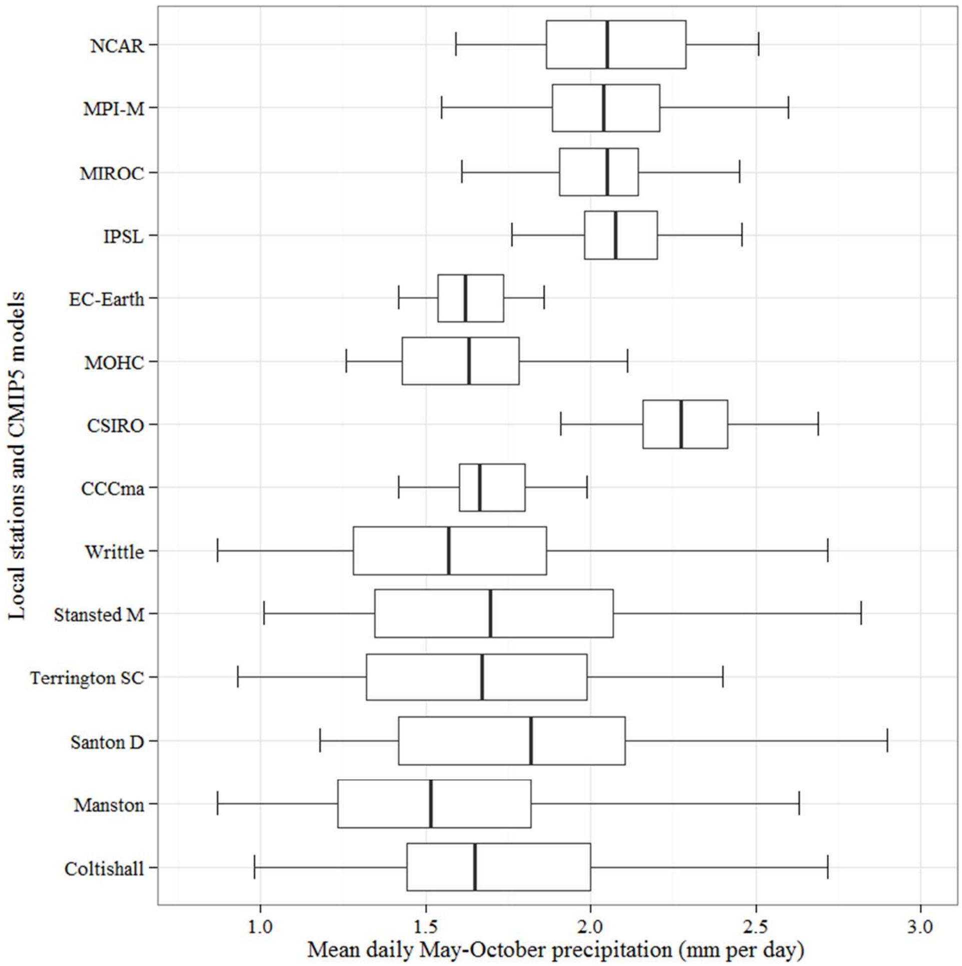

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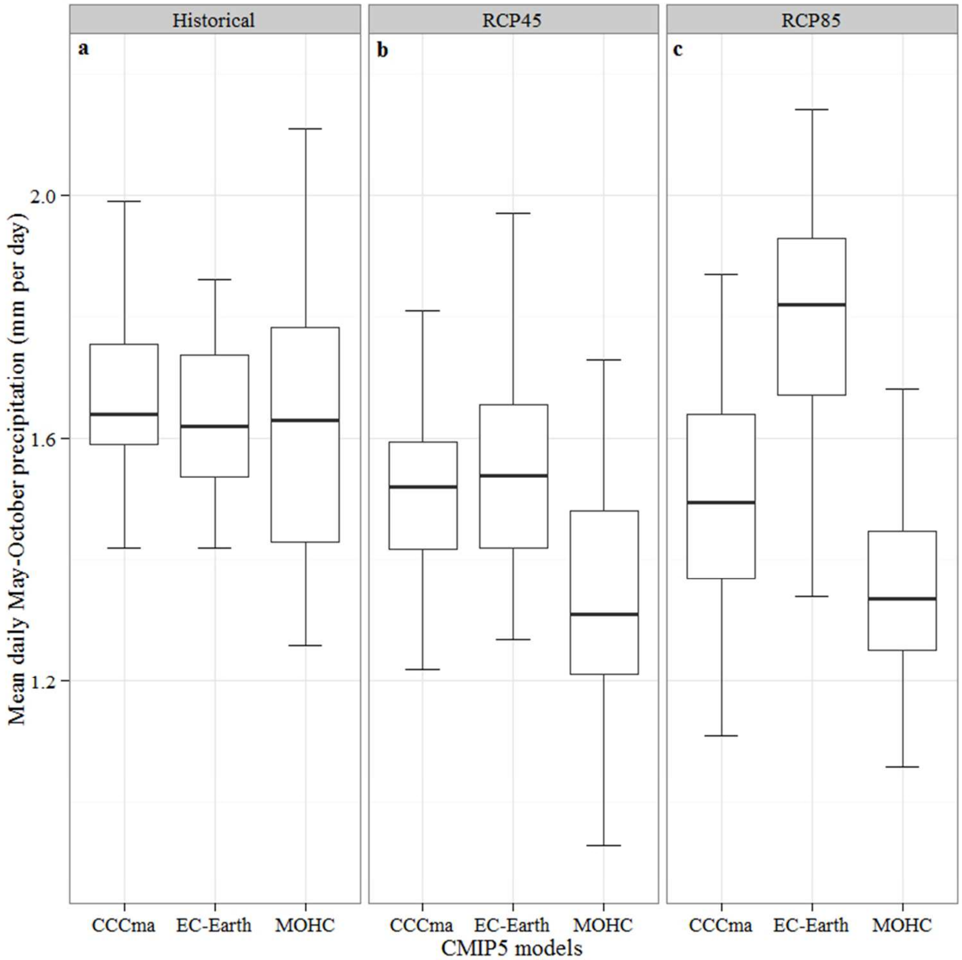

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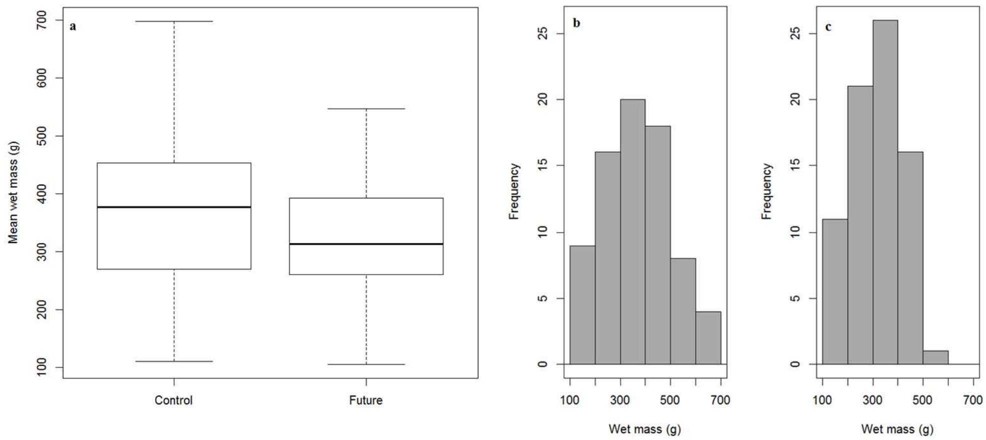
177x177mm (120 x 120 DPI)



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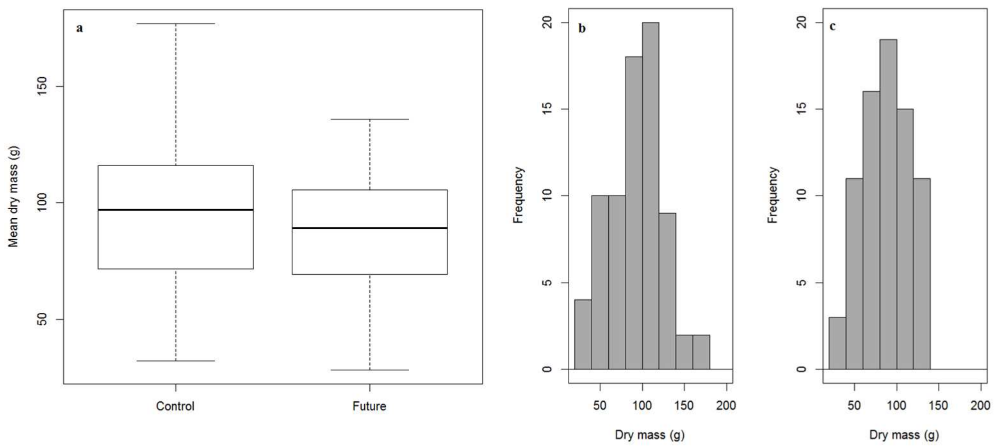

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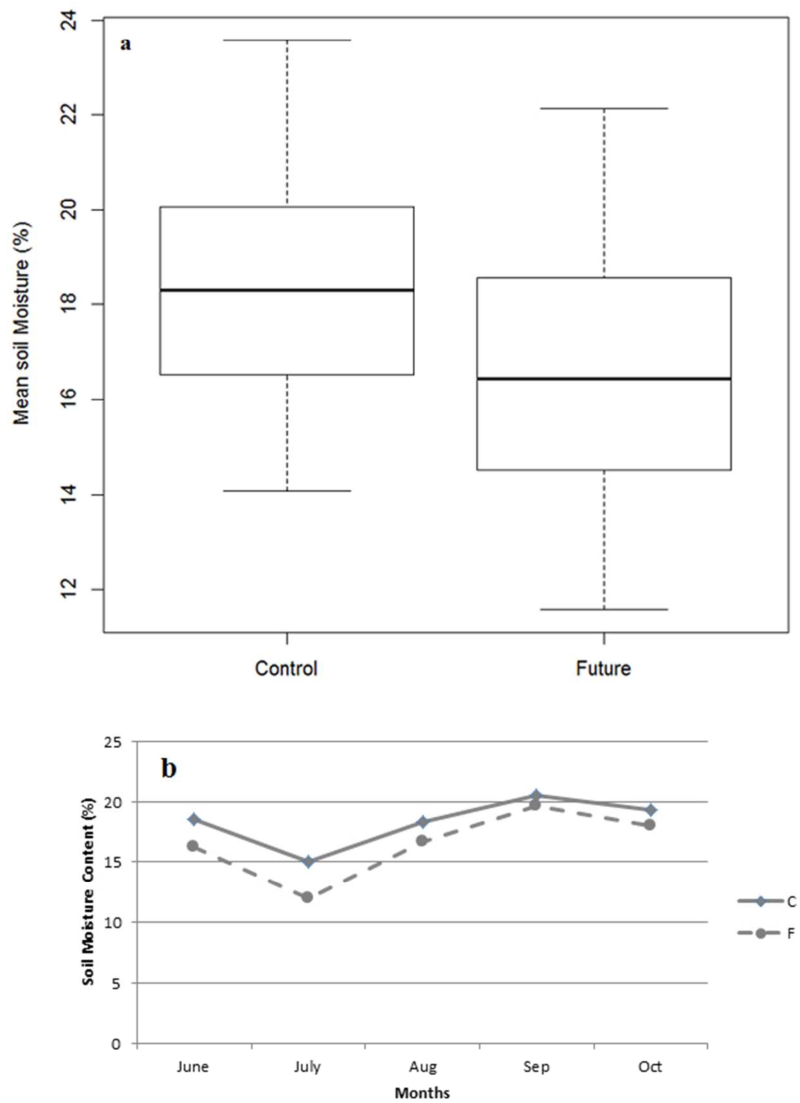

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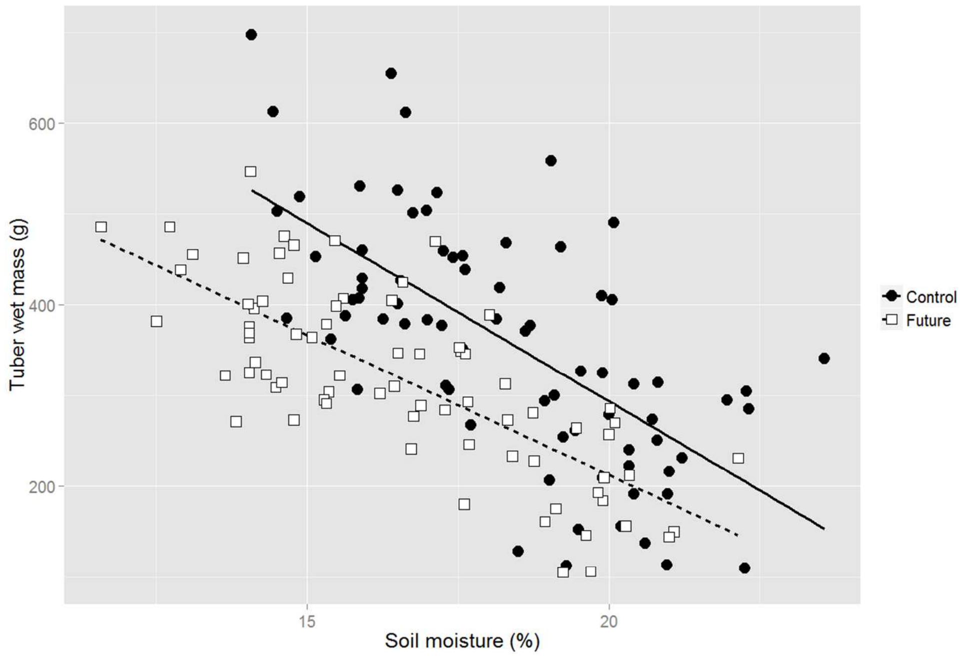

Figure 7: Scatter plot showing the “wet” mass for individual tubers from the “control” (filled circles; solid line) and “future” (open squares; dashed line) categories plotted against the mean soil moisture data for each replicate.
263x177mm (120 x 120 DPI)